WP4: Network-aware control and estimation

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Deliverables

Deliverables:

• D4.1. Analysis methods for networked control systems (M12). FINISHED

• D4.2. Synthesis methods for distributed MPC control and estimation algorithms using WSN (M24). FINISHED

• D4.3. Collection of prototype design tools in MATLAB™ for control and estimation with WSN in the loop (M36). FINISHED
D4.3. Collection of prototype design tools in MATLAB™ for control and estimation with WSN in the loop (M36).

- Further development of the methodologies (Task 4.2)
  - Modeling and Analysis of NCS
    - Robust
    - Stochastic
  - Design of Net-Aware State FB Control Algorithms
    - Centralized
    - Decentralized
  - Estimation for systems with unreliable networks
    - Optimal Kalman Filter
    - Suboptimal Kalman Filter
  - Decentralized Observer-Based Control
  - Event-triggered control algorithms
    - Centralized MPC
    - Decentralized
    - Periodic event-triggered
- Last period development of prototype design tools
Networked Control Systems
Unreliable networks

• Varying delays
• Packet loss
• Varying sampling periods
• Communication constraints: MAC protocols
• Quantization
Multi-disciplinary design

Net-aware control design
Two general frameworks handling all five network-induced phenomena

### SLPV models

\[
x_{k+1} = A(\sigma_k, \theta_k)x_k + B(\sigma_k, \theta_k)u_k \\
y_k = Cx_k + Du_k
\]

- \(x_k \in \mathbb{R}^n\) internal state
- \(y_k \in \mathbb{R}^p\) measured outputs
- \(u_k \in \mathbb{R}^m\) continuous control command
- \(\sigma_k \in \mathbb{N}\) discrete variable (related to protocol)
- \(\theta_k \in \mathbb{R}^r\) network-induced uncertainties (e.g., delay)
- \(A(\sigma, \theta) \in \mathbb{R}^{n \times n}, B(\sigma, \theta) \in \mathbb{R}^{n \times m}\) for \(\sigma \in \mathbb{N}, \theta \in \mathbb{R}^r\)
- \(C \in \mathbb{R}^{p \times n}, D \in \mathbb{R}^{p \times m}\)

### HI models

\[
\dot{x} = F(x), \text{ when } x \in C \\
x^+ = G(x), \text{ when } x \in D
\]

- \(x \in \mathbb{R}^n\) (containing discrete variables as well)
- \(C \subseteq \mathbb{R}^n\) (depending on bounds of imperfections)
- \(D \subseteq \mathbb{R}^n\) (depending on bounds of imperfections)
- \(F : \mathbb{R}^n \to \mathbb{R}^n\) (containing control and protocol parameters)
- \(G : \mathbb{R}^n \to \mathbb{R}^n\) (containing control and protocol parameters)
Tradeoffs: HI models (Robust)

- General approach: general NL systems / protocols

- Polynomial systems and piecewise polynomial protocols:
  [N.W. Bauer, P. Maas and W.P.M.H. Heemels, Stability Analysis of Networked Control Systems: A Sum of Squares Approach, Accepted Automatica.]
SLPV Framework

- **Discrete-time model of NCS**

\[
\begin{bmatrix}
    x_{k+1} \\
    u_k
\end{bmatrix} =
\begin{bmatrix}
    e^{Ah_k} & \int_{h_k}^{h_k} e^{As} ds B \\
    0 & 0
\end{bmatrix}
\begin{bmatrix}
    x_k \\
    u_{k-1}
\end{bmatrix} +
\begin{bmatrix}
    \int_{h_k}^{h_k} e^{As} ds B \\
    I
\end{bmatrix} u_k
\]

which is controlled using state-feedback controller

\[ u_k = K x_k \]

**Problem:**

\( h_k \) and \( \tau_k \) lie in continuous set \( H \)

→ infinite switching sequences!

**Solution:**

Embed the matrix uncertainty set in a polytopic set \( H \)

→ finite switching between vertices!

Choose vertices such that uncertainty set is embedded
D4.3 Different methods available for analysis and synthesis

- Methods for obtaining polytopic overapproximations based on
  - Interval matrices
    (Cloosterman, van de Wouw, Heemels, Nijmeijer, CDC 2006)
  - Real Jordan form
  - Cayley-Hamilton theorem
    (Gielen et al, NMPC 2008, Automatica 2010)
  - Taylor series
    (Hetel, Daafouz, Iung, TAC 2007)
  - Gridding (and norm bounding of approximation error)
    (Balluchi et al, HSCC 2005), (Fujuoka, ACC 2008), (Suh, Automatica 2008), (Donkers et al, HSCC 2009), (Skaf, Boyd, TAC 2009), (Dritsas et al, IJC, 2009)

[Heemels et al, Comparison, HSCC, Stockholm 2010]

Several methods implemented in the WIDE toolbox
D4.3 Comparison different methods

The overapproximation methods differ in

- **Computational complexity**
- **Approximation error / conservatism**

depending on the specific system dynamics!
Tradeoffs: SLPV models (Robust)

- SLPV approach tailored to linear plants and controllers
- Less conservative in this case

[S. van Loon, M.C.F. Donkers, N. van de Wouw, and W.P.M.H. Heemels, Stability analysis of networked control systems with periodic protocols and uniform quantizers, submitted]

- Extensions towards NL systems using approximately discretized models

[N. Van De Wouw, D. Nesic and W.P.M.H. Heemels, Automatica 2012]
Stochastic models

• Model of the NCS of the form
  \[ \xi_{k+1} = A_{h_k,\tau_k}^0 \xi_k + B_{h_k,\tau_k}^0 u_k \]
  with \[ \xi_k = \left[ x_k^i \quad u_{k-1}^i \right]^\top \]

• Not directly amendable for controller synthesis, therefore
  \[ \{(A_{h_k,\tau_k}^0, B_{h_k,\tau_k}^0) \mid (h_k, \tau_k) \in S_m \} \subset co\{(A_i, B_i) \mid i \in \{1, \ldots, 2^{2^\nu}\} \} \]

• Checkable conditions can now be derived in terms of LMIs, for both
  state-feedback controllers and output-based controllers

[Donkers, Heemels, Bernardini, Bemporad, Shneer, Automatica, to appear]
Tradeoffs: SLPV models (Stochastic)

- Benchmark example of unstable (linear) chemical batch reactor
- Consider time-varying sampling intervals only

- In Donkers, *et.al.* TAC 2011, MATI of 0.066 was obtained
- Interestingly: the Lyapunov function that is obtained for the state-feedback controlled system can also be used for SMPC design
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Network-aware state feedback

- **Centralized approaches**
  - Robustly stabilizing linear state feedback design for NCS
    
    \[\text{[Cloosterman, Hetel, vdWouw, Heemels, Daafouz, Nijmeijer, Automatica, 2010]}\]
  - Stochastic MPC of Stochastic NCS

- **Decentralized approaches**
  - Constrained linear state feedback
  - DMPC of coupled linear systems
Network-aware state feedback:  
(MPC of) Stochastic Networked Control Systems

• The NCS consists of LTI plant and state-feedback controller
• Because of the network:
  – Communication constraints
  – Time-varying sampling intervals
  – and time-varying delays
  – (and packet dropouts)

• These effects can often be regarded as an iid random process
  – We consider continuous pdfs (!)
Network-aware state feedback:
MPC of Stochastic Networked Control Systems

- Prediction model, based on averaged dynamics, is built on a different partition of the \((h, \tau)\) space
- This allows decoupling between stability requirements and performance optimization
- Online, a multiple-horizon optimization tree is built to minimize the (approximated) expected performance criterion
- Mean-square stability is guaranteed by quadratic constraints

[Bernardini, Donkers, Bemporad, Heemels, NECSYS 2010]
Network-aware state feedback: Constrained decentralized linear state feedback

- Network modeled as sets of sensors and actuators, whose information exchanges may go through reliable or unreliable connections;
- Goal: synthesize a decentralized state feedback control law which stabilize the linear plant, while enforcing constraints on both input and state;
- Decentralization is guaranteed by imposing a structure on the centralized feedback gain, i.e. set to 0 the element whose feedback is unavailable;

Two Approaches:
- **Robust approach**: consider all possible realization of the network connections, which is 2 power the number of unreliable links, and synthesize a gain for each configuration;
- The resulting switching controller enforces stability for each measurements reception occurrence

[Barcelli, Bernardini, Bemporad, CDC 2010]
Network-aware state feedback:
Constrained decentralized linear state feedback

• **Stochastic approach**: exploit the possibly available information about the packet-loss probability by defining a Markov chain model, which is characterized by transition and emission matrices;

• A controller is synthesized for each configuration that may occur in each of the two Markov chain states, leading to at least twice the synthesis complexity of robust case.

• Markov chain state is assumed to be known at the current time step.

• Stability is enforced though switching stochastic Lyapunov functions, which lead to consider Mean Square stability and soft constraints.

**Simulation results**

Cumulated storage cost

\[ J_i = \sum_{t=1}^{T_{sim}} (\|Q_x x(t)\|_2 + \|Q_u u(t)\|_2) \]

<table>
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<tr>
<th></th>
<th>( \mu(J_i) )</th>
<th>( \sigma(J_i) )</th>
<th>CPU</th>
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<tr>
<td><strong>Ideal network</strong></td>
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<tr>
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<td>0</td>
<td>1.2 s</td>
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<td><strong>Lossy network</strong></td>
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<td>(off-line time)</td>
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<tr>
<td>Dec. robust control</td>
<td>50.0</td>
<td>1.57</td>
<td>8.1 s</td>
</tr>
<tr>
<td>Dec. stochastic control</td>
<td>47.1</td>
<td>2.38</td>
<td>59.2 s</td>
</tr>
</tbody>
</table>

[Barcelli, Bernardini, Bemporad, CDC 2010]
Network-aware state feedback: 
DMPC of Dynamically-Coupled Linear Systems

• Plant: LTI input constrained system;
• Decentralization constraints:
  – all states have to be represented in at least one controller model
  – each input can be actuated by only one controller;
• Decentralized models, used for predictions, are obtained by selecting components from plant matrices accordingly with the decentralization:

\[ x^i(t + 1) = A_i x^i(t) + B_i u^i(t) \]

• Each controller solves an on-line optimization problem based on its related Lyapunov equation, given by

\[ A_i^T P_i A_i - P_i = -W_i^T Q W_i \]

• Convergence properties of the closed-loop system in case of unreliable connections can be studied

[Barcelli, Bemporad, Ripaccioli, IFAC Workshop on Estimation and Control of Networked Systems, 2009]
D4.3. Collection of prototype design tools in MATLAB™ for control and estimation with WSN in the loop (M36).

- Further development of the methodologies (Task 4.2)
  - Modeling and Analysis of NCS
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Network-aware estimation
Optimal Kalman filter for systems with communication delays

- **State estimation with process data transmitted over the network**
  - Delayed and lost packets.

- **Assumptions**
  - Delays integer multiples of sampling intervals
  - Data transmitted with their time stamps.

- **Optimal estimator** – **time varying**
  Kalman filter for system augmented by delays
  - Finite length of delay chain; longer delays → lost data.
  - Samples may arrive out of order, with several different time-stamps at a time.

- **New implementation of KF for this class of systems** – lower computational demand
  - A set of pre-computed gains
  - Recasting Riccati equation into a dynamical equation for a reduced-rank matrix factor

- **Further assumption:** **lossless network**
  - Samples arrive within max delay

- **Reduced dimension of the state-space**
  - Only missing measurements have to be included

- **Finite number of Kalman gains**
  - One per each configuration of missing data.

[Baramov, Pachner & Havlena: Kalman Filter for Systems with Communication Delays, NecSys 2009]
Network-aware estimation

Suboptimal Kalman Filter

• **Problem formulation**
  – Sensor measurements randomly delayed & time-stamped
  – Actuator moves acknowledged. Both command and acknowledgements subject to random communication delays.

• **Linear models:** the augmented state, time-varying Kalman filter is optimal
  – an overkill for PID loops.

• **Suboptimal solution:**
  – Missing values are replaced by estimates.
  – When the missing value arrives, the effect of value replacement is removed and the delayed item correctly applied.
  – The estimator is optimal when less than $N$ values is missing, $N$ can be chosen between zero and max
  – This state observer is a time invariant switched system – pre-computed Kalman gains are used

Simulation results: 90% samples delayed

- 1 optimal estimate
- 2 measurements replaced
- 3 delayed data ignored
- 4 time stamps ignored

[Simulation graph showing mean estimation error vs. maximum delay]

[Pachner, Baramov, Havlena: Suboptimal state estimation under communication delays, IFAC TDS10]
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Network-aware Observer-Based Control: Decentralized Observed-Based Control of Large-Scale Networked Systems

We consider decentralized control design and stability analysis for

- large-scale continuous-time linear plant
- via a multi-purpose network with
  - communication constraints: not all outputs and inputs can be communicated simultaneously
  - uncertain time-varying transmission intervals $h_k \in [\underline{h}, \overline{h}] \forall k \in \mathbb{N}$
Network-aware Observer-Based Control: Decentralized Observed-Based Control of Large-Scale Networked Systems

• The controllers:
  • observer-based with observer-gains $L_{i}$ and state fb gains $K_{i}$
  • decentralized – no sharing information
  • robust to bounded varying sampling intervals (and delays)
  • switch based on protocol (which sensor/actuator node communicates)
• Modeled with SLPV framework
• Stability can be proven via LMIs based on overapproximations
• Under simplifying assumptions (ignoring coupling / varying sampling intervals) LMI-based design possible
• Design can be achieved with LMI conditions based on overapproximations!

[Bauer, Donkers, vdWouw, , Heemels, submitted ACC12, journal]
Network-aware Observer-Based Control: Decentralized Observed-Based Control of Large-Scale Networked Systems

$h_{kl} \in [(1-\delta)h_{kl}^*, (1+\delta)h_{kl}^*]$ 

[Bauer, Donkers, vdWouw, , Heemels, submitted ACC12, journal]
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Event-triggered control

Objective:

- Mitigate unnecessary use of network resources (bandwidth, batteries)
- Keep satisfactory closed-loop stability and performance

→ Act only when needed!

- Active “control” of network
Network-aware state feedback: Energy-aware MPC

- Radio is the dominant power hog in a wireless sensor
- Control strategy should keep the radio off as much as possible

- Idea: transmit *only when necessary*, according to a threshold logic

  \[ y(k) \text{ is transmitted} \iff |y(k) - \hat{y}(k)| > \varepsilon \]

- Sequences of predictions \( \hat{y}(k+1|k), \hat{y}(k+2|k), \ldots, \hat{y}(k+M|k) \) are computed by the controller beforehand and sent to sensors
- Trade-off: transmission rate vs closed-loop performance
Network-aware state feedback: Energy-aware MPC

- When controller receives measurements, it transmits a new set of $M$ predictions
- In the ideal case of no disturbance, the transmission rate is $1/M$
- *Idle listening* is minimized

- Examples show promising trade-off: substantial reduction in tx rate ($\sim 45\%$) with small loss in performance ($<2\%$)
- Robust stability can be obtained via explicit min-max formulations

[Bernardini, Bemporad, Automatica 2011]
Decentralized event-triggered control

- Decentralized event-triggering mechanisms for linear plants and controllers
- First output-based
- Improved ETMs with guarantee stability/performance (HI models)

[M.C.F. Donkers and W.P.M.H. Heemels, "Output-Based Event-Triggered Control with Guaranteed $L_\infty$-gain and Improved and Decentralised Event-Triggering", TAC 2012]
Periodic event-triggered control

• Combine best of two worlds:
  – Time-triggered periodic sampled-data control
  – Event-triggered control

• Complete analysis and design framework

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- Last period development of prototype design tools
WIDE toolbox

• **Collection of Design Tools:**
  – Large Scale Model Management (Honeywell);
  – Decentralized and Hierarchical MPC (Unisi/Unitn)
  – Kalman Filter tools (HPL)
  – Networked Control System (TU/e);

• **Documentation:**
  – Automatically generated with Publish Matlab function, thus included in the download;
  – Living WEB wiki: [http://cse.lab.imtlucca.it/HYCON2/index.php/Wide_main](http://cse.lab.imtlucca.it/HYCON2/index.php/Wide_main)
  – Download: [http://ist-wide.dii.unisi.it/](http://ist-wide.dii.unisi.it/)
WIDE toolbox: Large Scale Model Management

- Represent and manage Large Scale (LS) models. A LS model is described as a set of submodels together with description of mutual and external inputs/outputs interconnections.

**Management Capabilities:**
- Model creation from a set of submodels, a set of summators and string cell arrays defining external inputs and outputs.
- Add/remove submodels and external inputs/outputs
- Model visualization

**Functions:**
- Structured model order reduction
- Decomposition of subsystems into groups
- Merging of information from multiple models into single one
- More model analysis via many standard functions

**Water Network Model:**
- Child of LS, extended to model water distribution networks
- Import scheme from text file, customized plot customized Epsilon decomposition procedure
WIDE toolbox: Decentralized and Hierarchical MPC

Energy-Aware MPC: implementation of an explicit MPC controller, where communications between controller and sensor nodes are subject to an energy-aware policy intended to lower the number of transmissions and, ultimately, prolong sensor battery lifetime.

DecLMI: is a framework that allows to synthesize a decentralized linear feedback which guarantees stability and constraint enforcements on a LTI plant despite network unreliability in an either robust or stochastic fashion.

TrueTime extension: TT is a very powerful tool which can handle simulation of a variety of tasks, with a particular focus on real-time implementation of controller code. However such flexibility implies a high setup complexity which prevent the user on just focusing on WSN issues. This toolbox section automatically generates the TrueTime code for a common, although customizable, network configuration allowing the user to exploit TT functionalities (interface).
WIDE toolbox: Network-Aware KF tools

- Set of S-functions implementing network-aware Kalman filters
  - New computation-effective implementation of optimal time-varying KF
  - Switched-gain optimal KF
    - Optimal under assumption that data arrive within maximum delay
    - Extremely computationally cheap
    - Combinatorial growth of pre-stored gains with max delay

- Sub-optimal switched gain
  - Computationally cheap
  - Reduced number of pre-computed gains

- Simulink Demos for evaluating effectiveness of net-ware KF in a SISO PID loop with communication delay
  - Including multi-hop network model
  - Alternative strategies for handling delays (Smith predictor)
  - Network-unaware strategies

Network-aware KF tools are included in WIDE toolbox
WIDE toolbox: Networked Control System

- **Purpose:** model, analyze and synthesize control of a linear time invariant plant over a network.

- **Modeling approaches:**
  - SLPV NCS model
  - HI NCS model

- **Modeled effects:**
  - varying transmission intervals
  - varying delays
  - dropouts
  - shared comm. medium

- **NCS Editor:**
  - Easily create NCS objects
  - Import/Export NCS models
  - Stability analysis with various overapprox. techniques
Different methods available for analysis and synthesis

- **Methods for obtaining polytopic overapproximations based on**
  - Interval matrices
    (Cloosterman, van de Wouw, Heemels, Nijmeijer, CDC 2006)
  - Real Jordan form
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[Heemels et al, Comparison, HSCC, Stockholm 2010]
## WIDE toolbox: Networked Control System

<table>
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<tr>
<th>Attribute</th>
<th>DLTI NCS Model</th>
<th>Hybrid NCS Model</th>
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<tbody>
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<tr>
<td>time-var. delays (small)</td>
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<td>$\mathcal{L}_p$ performance</td>
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<td>★</td>
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</tbody>
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Dissemination Activities for WP4

• Lectures at various summer schools (Siena, Trento, Gummersbach)
• WIDE BOOK
• Minicourse on NCS by TU/e on Benelux Meeting on Systems and Control 2010, Heeze, The Netherlands (150 attendants)
• National PhD course within the Dutch Institute of Systems and Control (DISC) by TU/e (ca. 35 PhD students from universities in the NL)
• Many publications (http://istwide.dii.unisi.it/index.php?p=publications)
  – 15 journal
  – 4 submitted journal
  – 3 book chapters
  – 30 conference
WP4 Conclusions

• Analysis and Design of Control Algorithm / MAC Protocol for systems with unreliable networks
  • Robust \ Stochastic
  • Centralized \ Decentralized

• Estimation for systems with unreliable networks
  • Optimal Kalman Filter
  • Suboptimal Kalman Filter

• Decentralized Observer-Based Control design

• Event-triggered control algorithms
  + Net-efficient (only use bandwidth when necessary)
  + Energy-efficient (battery-powered devices)

• Toolbox implementation

• Deliverables completed
• Lots of dissemination